INTEGRATED ELECTRONICS: ANALOG AND DIGITAL CIRCUITS AND SYSTEMS

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and the low-frequency gain with feedback $A_{Vf} = -95.68$, or 39.61 dB. The complete response is shown in Fig. 14-27.

c. From the plot of part *b* we see that the voltage gain peaks at $f_o = 8$ MHz. If we place the zero of the β network at f_o, we find

$$C_f = \frac{1}{2\pi R_f f_o} \approx 4 \text{ pF}$$

The frequency response of A_{Vf} with $R_f = 5$ K and $C_f = 4$ pF is plotted in Fig. 14-27, from which we see that there is no peaking.

14-15 SINUSOIDAL OSCILLATORS

Many different circuit configurations deliver an essentially sinusoidal output waveform even without input-signal excitation. The basic principles governing all these oscillators are investigated. In addition to determining the conditions required for oscillation to take place, the frequency and amplitude stability are also studied.

Figure 14-28 shows an amplifier, a feedback network, and an input mixing circuit not yet connected to form a closed loop. The amplifier provides an output signal x_o as a consequence of the signal x_i applied directly to the amplifier input terminal. The output of the feedback network is $x_f = \beta x_o = A\beta x_i$, and the output of the mixing circuit (which is now simply an inverter) is

$$x'_f = -x_f = -A\beta x_i$$

From Fig. 14-28 the loop gain is

$$\text{Loop gain} = \frac{x'_f}{x_i} = \frac{-x_f}{x_i} = -\beta A \qquad (14\text{-}59)$$

Suppose it should happen that matters are adjusted in such a way that the signal x'_f is *identically* equal to the externally applied input signal x_i. Since the amplifier has no means of distinguishing the source of the input signal applied to it, it would appear that, if the external source were removed and if terminal 2 were connected to terminal 1, the amplifier would continue to

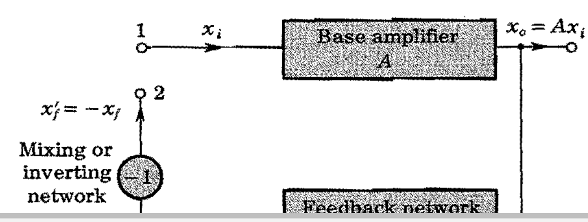

Fig. 14-28 An amplifier with transfer gain A and feedback network β not yet connected to form a closed loop. (Compare with Fig. 13-8.)

provide the same output signal x_o as before. Note, of course, that the statement $x'_f = x_i$ means that the instantaneous values of x'_f and x_i are exactly equal at all times. Note also that, since in the above discussion no restriction was made on the waveform, it need not be sinusoidal. The amplifier need not be linear, and the waveshape need not preserve its form as it is transmitted through the amplifier, provided only that the signal x'_f has the waveform and frequency of the input signal x_i. The condition $x'_f = x_i$ is equivalent to $-A\beta = 1$, or *the loop gain must equal unity.*

The Barkhausen Criterion We assume in this discussion of oscillators that the entire circuit operates linearly and that the amplifier or feedback network or both contain reactive elements. Under such circumstances, the only periodic waveform which will preserve its form is the sinusoid. For a sinusoidal waveform the condition $x_i = x'_f$ is equivalent to the condition that the *amplitude, phase,* and *frequency* of x_i and x'_f be identical. Since the phase shift introduced in a signal in being transmitted through a reactive network is invariably a function of the frequency, we have the following important principle:

The frequency at which a sinusoidal oscillator will operate is the frequency for which the total shift introduced, as a signal proceeds from the input terminals, through the amplifier and feedback network, and back again to the input, is precisely zero (or, of course, an integral multiple of 2π). Stated more simply, the frequency of a sinusoidal oscillator is determined by the condition that the loop-gain phase shift is zero.

Although other principles may be formulated which may serve equally to determine the frequency, these other principles may always be shown to be identical with that stated above. It might be noted parenthetically that it is not inconceivable that the above condition might be satisfied for more than a single frequency. In such a contingency there is the possibility of simultaneous oscillations at several frequencies or an oscillation at a single one of the allowed frequencies.

The condition given above determines the frequency, provided that the circuit will oscillate at all. Another condition which must clearly be met is that the magnitude of x_i and x'_f must be identical. This condition is then embodied in the following principle:

Oscillations will not be sustained if, at the oscillator frequency, the magnitude of the product of the transfer gain of the amplifier and the magnitude of the feedback factor of the feedback network (the magnitude of the loop gain) are less than unity.

The condition of *unity loop gain* $-A\beta = 1$ is called the *Barkhausen criterion.* This condition implies, of course, both that $|A\beta| = 1$ and that the phase of $-A\beta$ is zero. The above principles are consistent with the feedback formula $A_f = A/(1 + \beta A)$. For if $-\beta A = 1$, then $A_f \rightarrow \infty$, which may be interpreted to mean that there exists an output voltage even in the absence of an externally applied signal voltage.

Practical Considerations Referring to Fig. 14-8, it appears that if $|\beta A|$ at the oscillator frequency is precisely unity, then, with the feedback signal connected to the input terminals, the removal of the external generator will make no difference. If $|\beta A|$ is less than unity, the removal of the external generator will result in a cessation of oscillations. But now suppose that $|\beta A|$ is greater than unity. Then, for example, a 1-V signal appearing initially at the input terminals will, after a trip around the loop and back to the input terminals, appear there with an amplitude larger than 1 V. This larger voltage will then reappear as a still larger voltage, and so on. It seems, then, that if $|\beta A|$ is larger than unity, the amplitude of the oscillations will continue to increase without limit. But of course, such an increase in the amplitude can continue only as long as it is not limited by the onset of nonlinearity of operation in the active devices associated with the amplifier. Such a nonlinearity becomes more marked as the amplitude of oscillation increases. This onset of nonlinearity to limit the amplitude of oscillation is an essential feature of the operation of all practical oscillators, as the following considerations will show: The condition $|\beta A| = 1$ does not give a range of acceptable values of $|\beta A|$, but rather a single and precise value. Now suppose that initially it were even possible to satisfy this condition. Then, because circuit components and, more importantly, transistors change characteristics (drift) with age, temperature, voltage, etc., it is clear that if the entire oscillator is left to itself, in a very short time $|\beta A|$ will become either less or larger than unity. In the former case the oscillation simply stops, and in the latter case we are back to the point of requiring nonlinearity to limit the amplitude. An oscillator in which the loop gain is exactly unity is an abstraction completely unrealizable in practice. It is accordingly necessary, in the adjustment of a practical oscillator, always to arrange to have $|\beta A|$ somewhat larger (say 5 percent) than unity in order to ensure that, with incidental variations in transistor and circuit parameters, $|\beta A|$ shall not fall below unity. While the first two principles stated above must be satisfied on purely theoretical grounds, we may add a third general principle dictated by practical considerations, i.e.:

In every practical oscillator the loop gain is slightly larger than unity, and the amplitude of the oscillations is limited by the onset of nonlinearity.

The treatment of oscillators, taking into account the nonlinearity, is very difficult on account of the innate perverseness of nonlinearities generally. In many cases the extension into the range of nonlinear operation is small, and we simply neglect these nonlinearities altogether.

14-16 THE PHASE-SHIFT OSCILLATOR[9]

We select the so-called *phase-shift oscillator* (Fig. 14-29) as a first example because it exemplifies very simply the principles set forth above. Here an